Novel Probes of Gravity and Dark Energy

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What's a novel probe

- A novel theory is one that accounts for cosmic acceleration but is not a smooth, dark energy model.
- Modified gravity, dark matter-dark energy coupling, dark energy-matter coupling: possibly connected effects!
- A novel probe is one that does not match onto the big imaging or spectroscopic survey program
- Novel theories are in some cases well tested by standard probes, in others they require a combination of new experiments and observations not usually considered dark energy probes.

The novel probes process, or lack thereof

- There has been impressive progress in testing novel theories via lab experiments, solar system, stars and galaxy observations

- Some of the ideas and tests point to a broad, robust program

- But a fair bit more work is needed to arrive at a coherent account.

- We'll have a workshop at Penn on April 26+27. Next steps will be taken April -> August.

how cosmological effects show up inside galaxies

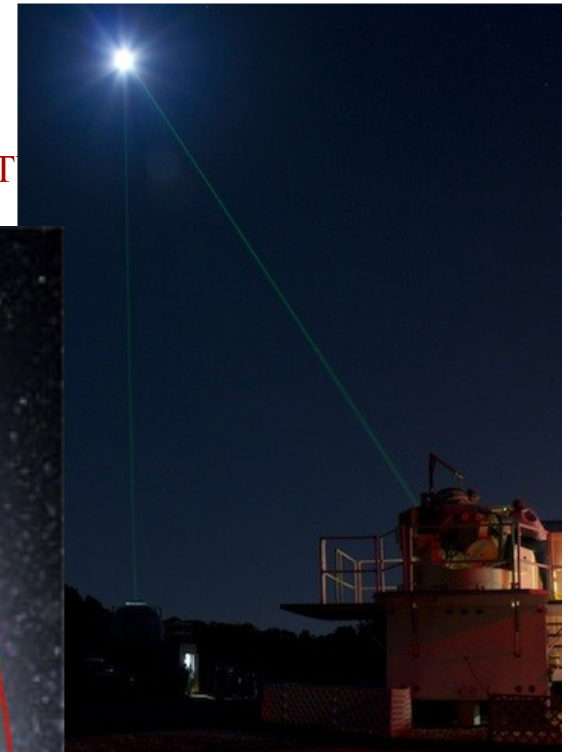
Why should we do weak field tests outside the solar system?

- **Generically** get scalar-tensor theories: scalar field provides an attractive, fifth-force (Theories:Vainshtein/DGP, Chameleon/f(R), Symmetron…)
  - $a = -\nabla(\Psi_S + \Psi_N)$, and $\Psi_S \sim \Psi_N$

⇨ This can enhance effective G & forces on galaxies by 10s of %

- GR restored in the Milky Way via **screening mechanisms** that work for massive/dense objects. *Vainshtein 72; Khoury & Weltman 2004*

New gravitational degrees of freedom that couple to matter (MODIFIED GRAVIT
are highly constrained: *Tolley slide*



Fifth Forces (solar system)

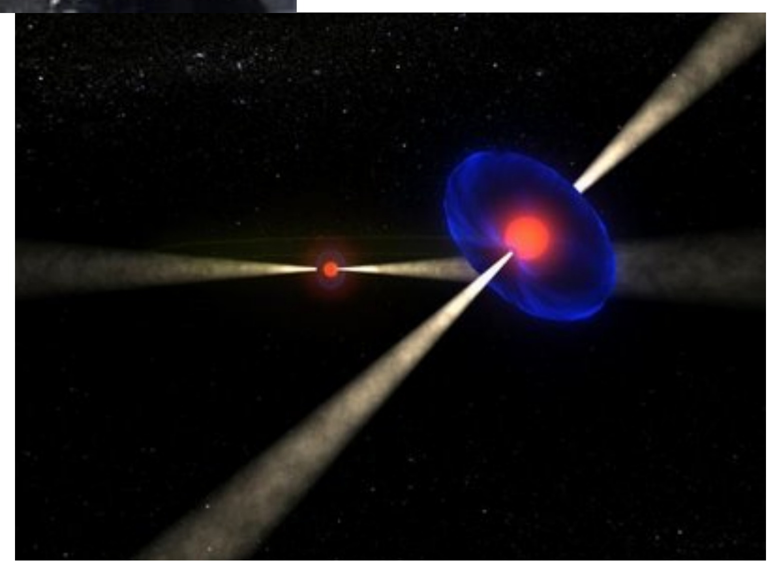
Equivalence Principle Tests etc.

Binary Pulsar Timing

Nucleosynthesis/Cosmology

Variation of fundamental constants

Need some kind of screening mechanism to hide extra d.o.f.



Modified Gravity

deviations from GR on different scales

Length scale:
100 Mpc

- Galaxy motions and lensing
  - Redshift space infall motions enhanced
  - Dynamical masses > Lensing masses
- Galaxy kinematics
  - Gas rotates faster than stars
  - Asymmetric rotation curves
- Galaxy morphology
  - Warped disks, aligned with fifth force
  - Stellar disk offset from gas
  - SMBH black holes offset from central starlight
- Stars
  - Cepheids pulsate faster: distance indicators test gravity!
- Solar system
- Laboratory

10^{-12} Mpc

Modified gravity involves new fields: interactions of new d.o.f. with matter in different screening mechanisms

Tolley slide

Imagine a scalar $\phi = \phi_b + \delta\phi$

coupled to the energy density $\rho = \rho_b + \delta\rho$

Generic form of equation of motion for perturbations

$$Z(\phi_b, \rho_b)\left[\frac{d^2\delta\phi}{dt^2} - c_s^2\frac{d^2\delta\phi}{dx^2}\right] + m^2(\phi_b, \rho_b)\delta\phi = \beta(\phi_b, \rho_b)G_{\mathrm{Newton}}\delta\rho$$

kinetic term

mass term

coupling to matter

gradient term

How does the fifth force get screened? *Tolley slide*

$$F \approx \frac{M_a M_b G}{r^2} \frac{\beta^2(\phi_b, \rho_b)}{\sqrt{Z}(\phi_b, \rho_b) c_s(\phi_b, \rho_b)} \exp(-m(\phi_b, \rho_b) r)$$

To ensure fifth forces are small

$$\frac{\beta^2(\phi_b, \rho_b)}{\sqrt{Z(\phi_b, \rho_b)} c_s(\phi_b, \rho_b)} \exp(-m(\phi_b, \rho_b) r)$$

Only three independent possibilities!

(a) Coupling is small $\quad \beta(\phi_b, \rho_b) \ll 1$

(b) Mass is large $\quad m(\phi_n, \rho_b) \gg \frac{1}{r_{exp}}$

(c) Kinetic term is large $\quad Z(\phi_b, \rho_b) \gg 1$

Looking for the fifth force: equivalence principle violations by stars, gas and dark matter

• Enhanced forces can alter the luminosities, colors and ages of stars in unscreened galaxies.

- Newtonian potential of Milky Way **and** of main sequence stars: $\psi \sim 10^{-6}$
- Giant stars may feel higher G_{eff}.

Chang & Hui 2010; Davis et al 2011; BJ, Vikram, Sakstein 2012

• Dark matter and gas clouds are diffuse -> should feel the fifth/scalar force if their host galaxy is unscreened.

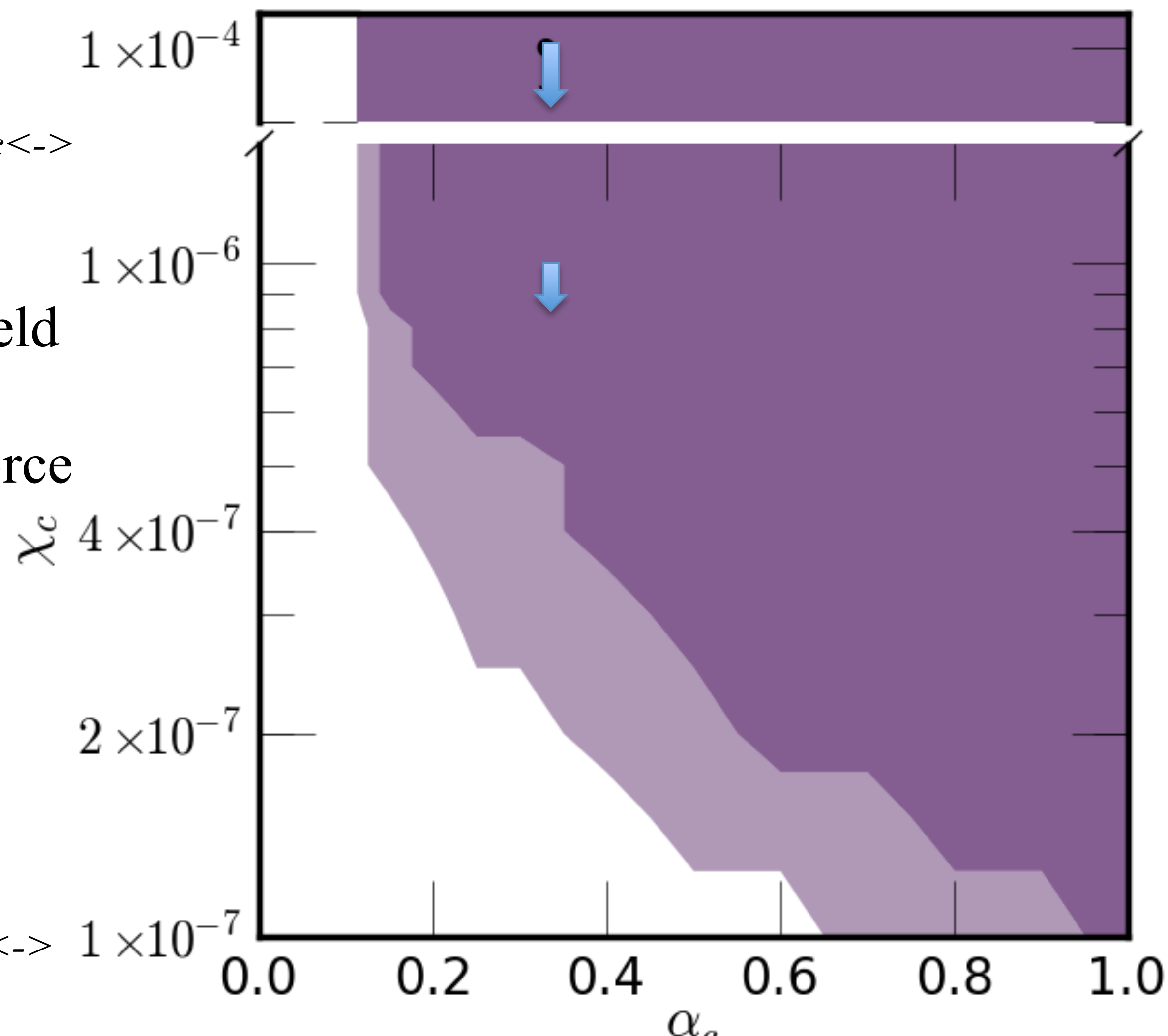
- Stars rotate slower and separate from gas due to external forces
- Black holes and stars may also separate in some scenarios

Hui, Nicolis & Stubbs 2009; BJ & VanderPlas 2011; Hui &Nicolis 2012

Gravity tests with cepheids/distance indicators

10 Mpc<->

Background field
or
Range of 5$^{\text{th}}$ force



1 Mpc<->

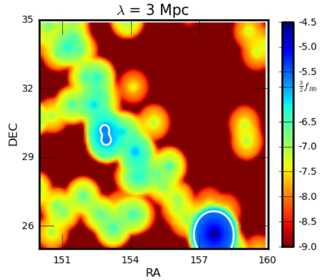
Coupling parameter of scalar to matter

BJ, Vikram & Sakstein 2012

Stars and galaxies at different scales: *Upadhye slide*

Next steps: Nonlinear structure in modified gravity

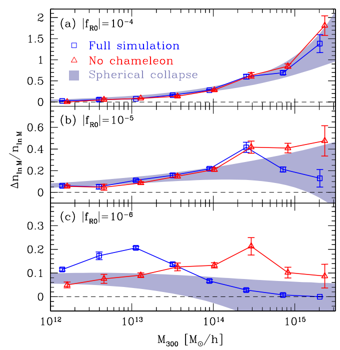
Stars in screened environments



Jain, Vikram, Sakstein, arXiv:1204.6044 (2012); *Cabre* et al., *JCAP* **1207***:34 (2012)[arXiv:1204.6046].*

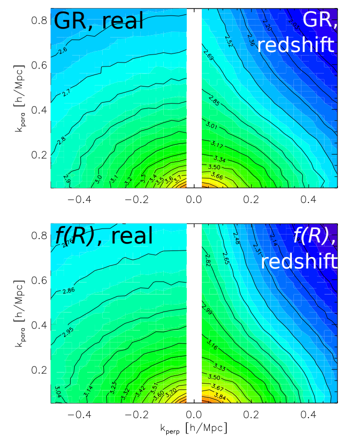
See Bhuvnesh's talk!

Cluster counts



Schmidt, Lima, Oyaizu, Hu, PRD **79***:083518 (2009)[arXiv:0812.0545].*, *Schimdt, Vikhlinin, Hu, PRD* **80***:083505 (2009)[arXiv:0908.2457].*

Red shift space distortions (RSD)

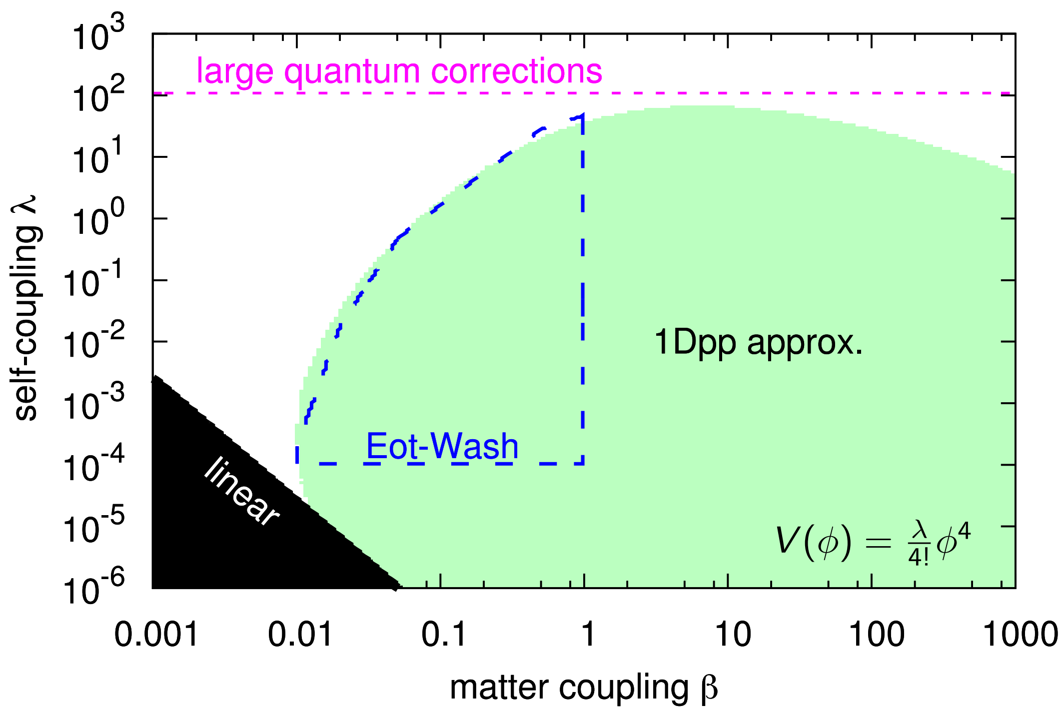


Jennings, et al., arXiv:1205.2698, to appear in MNRAS (2012)

Laboratory tests of scalar fields: I

Upadhye slide

Eöt-Wash constraints on chameleons



Eöt-Wash: *Adelberger, Heckel, Hoedl, Hoyle, Kapner, AU. PRL* **98** *131104 (2007)*
1Dpp: *AU, PRD* **86** *102003 (2012) [arXiv:1209.0211]*

Also, dark energy-photon coupling, Casimir experiments, cold neutrons,

Laboratory tests of scalar fields: II

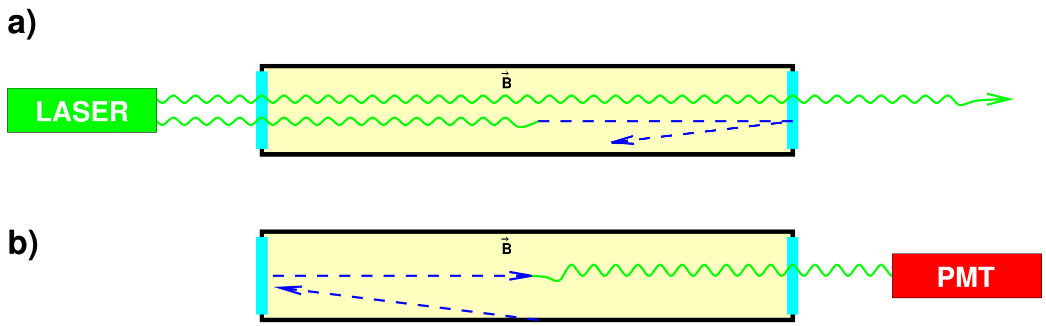
Upadhye slide

How dark is dark energy? DE-photon couplings

A photon coupling term $\frac{\beta_\gamma}{4M_{\rm Pl}}F_{\mu\nu}F^{\mu\nu}\phi$ means that dark energy particles can be produced through oscillation in a magnetic field.

The CHASE afterglow experiment has two phases:

(a) Production phase: photons streamed through $\vec{B}_0$ region; some oscillate into chameleons



(b) Afterglow phase: chameleons slowly oscillate back into photons, escaping chamber

Varying constants: *Thompson slide*

Here we treat only dimensionless constants as fundamental constants such as

$\propto = 2\pi e^{2}/hc$ or $\mu = m_{P}/m_{e}$

Any civilization that can count will come up with the same numbers

We will concentrate on μ but $\propto$ conforms to the same physics.

We will consider rolling scalar fields that couple with gravity to accelerate the expansion of the universe and that also couple with the electromagnetic field.

Inputs: *Thompson slide*

Redshifted H2 lines

Optical

CH3OH, NH3

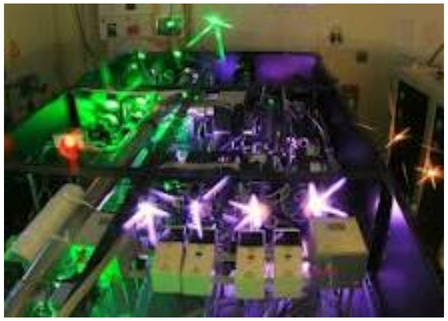
Radio

$\Delta\mu/\mu$, $\Delta\alpha/\alpha$

Lab

Lab $\Delta\mu$, $\Delta\alpha$ Measurements

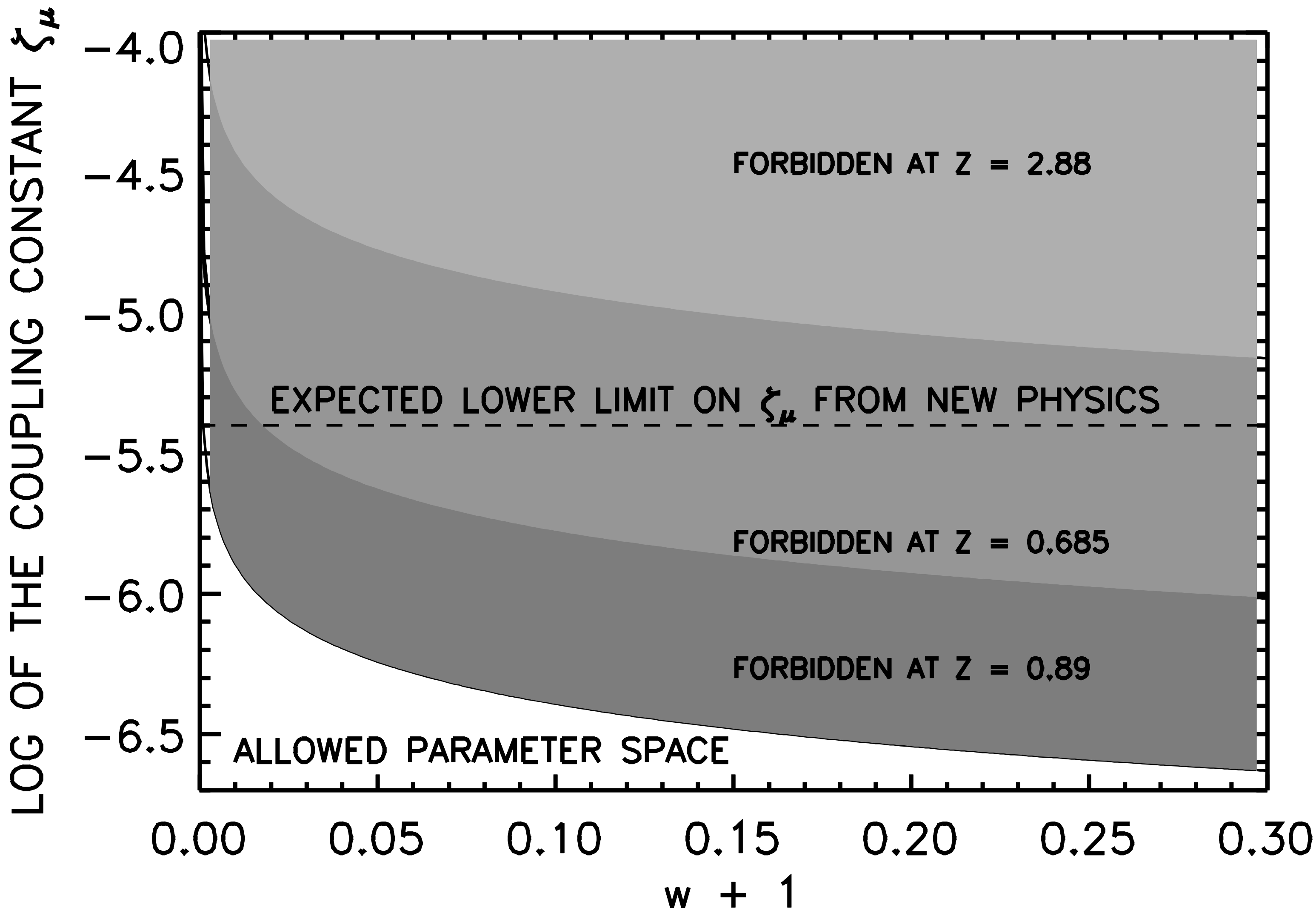
Lab



Precise Wavelengths

New Excluded Parameter Space:

Thompson slide



What next for gravity tests?

- What kind of gravity test will be most powerful?
  - Depends on the theory, so need to keep an open mind. But screening mechanisms are generic and signatures of different mechanisms are already known.
  - Lab, solar system, stellar, galaxy and larger scale tests all have potential
- What can we do next for astrophysical tests?
  - Two regimes of astro tests:
    - local universe (within a few 100 Mpc), where a full map of the environment of galaxies can be used for tests with small samples of galaxies
    - low redshift (~0.2) universe where lensing and dynamics can be studied for a range of galaxy types
  - Study the instrumental capabilities for studying individual galaxies via: (a) high resolution imaging, (b) spectroscopy and (c) radio observations of HI disks
  - Scope out other tests, such as via pulsars and supermassive black holes, and figure out the instrumental needs
  - Develop detailed predictions for screening mechanisms: how well can this be done without full models?
- Cosmological scale tests will be carried out by surveys already planned. Work needed on fashioning tests of gravity and combining with tests on other scales.

- A novel theory is one that accounts for cosmic acceleration but is not a smooth, dark energy model.
- Modified gravity, dark matter-dark energy coupling, dark energy-matter coupling: possibly connected effects!
- A novel probe is one that does not match onto the big imaging or spectroscopic survey program
- Novel theories are in some cases well tested by standard probes, in others they require a combination of new experiments and observations not usually considered dark energy probes (e.g. MANGA):
  - Laboratory experiments
  - Observations of small, nearby galaxies
  - Lensing, dynamics and morphologies of low-redshift galaxies

Novel Probes

Workshop at U Penn

April 26, 27

Day 1 ->

Please email me if

you're interested:

bjain@physics.upenn.edu

1. Introduction Session:
What are novel probes of gravity and dark energy?
Theories of modified gravity
Overview of experimental results from lab, solar system, galaxy and cosmological scales

2. How gravity theories recover GR in the solar system: new small scale tests
Screening mechanisms: the basic variants of screening and their qualitative behavior
 - Chameleon et al
 - Vainshtein
Discussion on observational implications: what are the distinct signatures of each class of gravity theories?

3. Gas, Stars and Black Holes as tests of gravity
Overview: why astrophysical tests matter
Observational tests using disk galaxies
Tests using stars and distance indicators

4. Lab, solar system and pulsar tests of gravity
Lab and solar system tests
Pulsar tests
Discussion: what tests of gravity are useful outside of the framework of validating GR (or PPN)?

Novel Probes

Workshop at U Penn

April 26, 27

Day 2 ->

Please email me if you're interested

1. Scalar field couplings: variation of fundamental constants and other tests
Theory and outlook
High redshift observations of molecular lines
Dwarf galaxies and dark matter: dark matter coupling, self interactions

2. Cosmological predictions of gravity theories
Linear perturbations in modified gravity: parameterization
Lensing, redshift space distortions and other large-scale probes
Discussion: what can we expect to learn in the next 5 years

3. Forthcoming observations and experiments:
New surveys: radio, spectroscopy, imaging
Pulsars and black holes

4. Discussion: New observations/experiments for the next generation of tests

- Spare slides

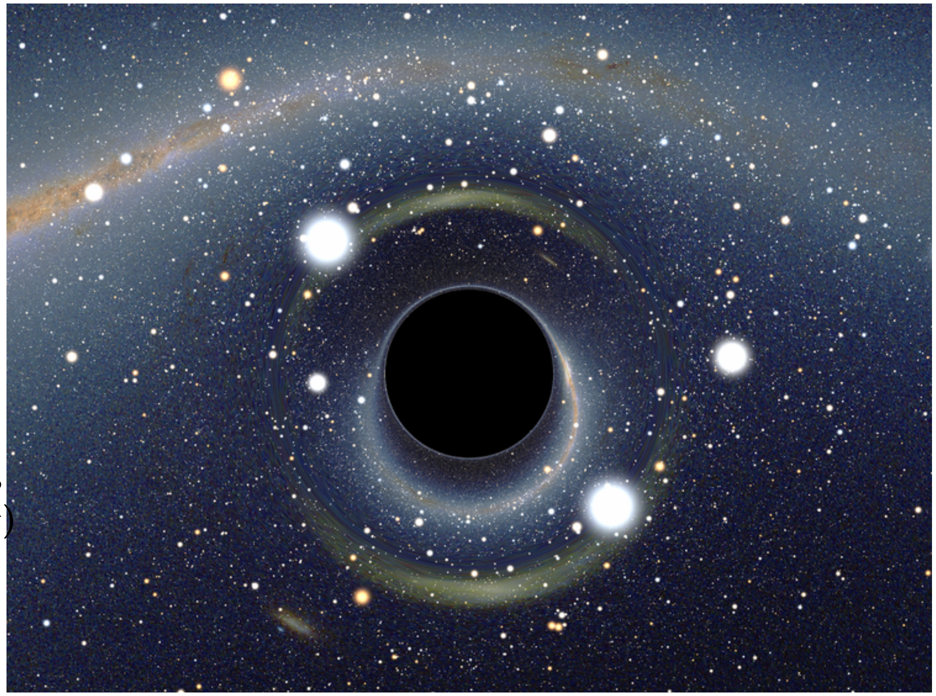
Black Holes: *Tolley slide*

On Black Holes in Massive Gravity
L. Berezhiani,G. Chkareuli, G. Gabadadze, C. de Rham, Phys.Rev. D85 (2012) 044024

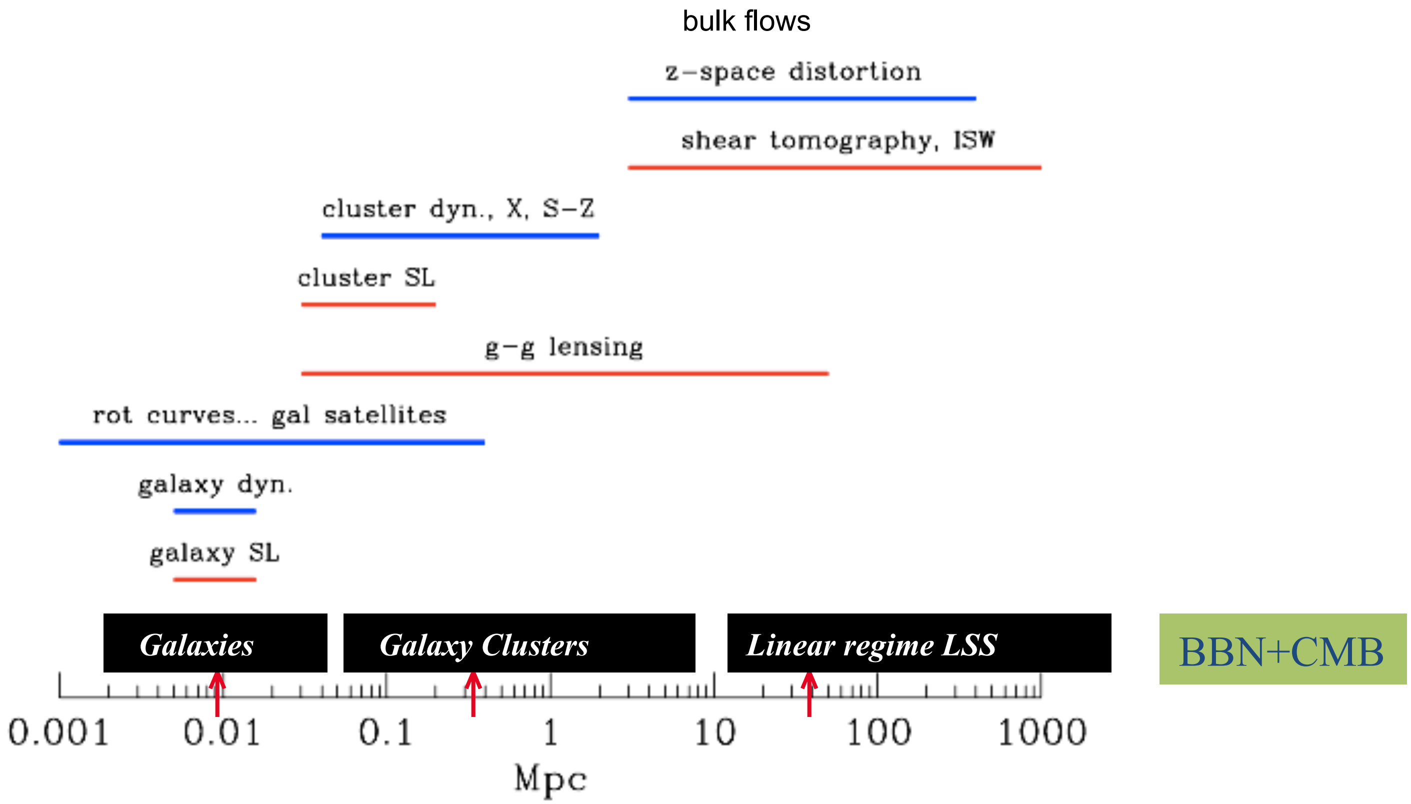
In Massive Gravity more than one effective metric:
waves travelling through a medium have a different velocity
Notion of causality is more subtle - scalar waves can travel faster or slower than tensor waves

Black hole horizons
are more complex than in GR

Near the BH horizon the Vainshtein mechanism ensures
the geometry is close to Schwarzshild (general relativity)



Astrophysical and cosmological probes of gravity



Dynamical probes (blue) measure Newtonian potential ψ

Lensing and ISW (red) measures $\phi + \psi$ *Jain & Khoury 2010*

Small Scale Tests at z>0.1: Einstein rings

$\gamma = \psi/\phi = 1.01 +/- 0.05$ from Einstein Rings + velocity dispersion

Error bars are statistical.

Bolton et al 2006; Schwab, Bolton, Rappaport 2010